Searches for SUSY

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Why look for SUSY after LHC Run1?

The main motivations remain

**Hierarchy problem**
- low-mass top squarks cancel SM contributions to $m(H)$
  ( + light higgsinos, gluinos )

**Unification of gauge couplings**
- Presence of sparticles changes running of couplings

**Dark matter**
- lightest SUSY particle can be massive, stable, and weakly interacting

With increasingly higher limits, in particular on top squarks, natural SUSY is under pressure ...

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NASA / Chandra
Limited time imposes a selection
Focus on most recent (2016) LHC results
( neglecting indirect limits / precision measurements )
Restrict to subset of models
( no long-lived particle searches, no generic
dark-matter interpretations )
SUSY in 13 TeV pp collisions

Considerably higher cross sections w.r.t. Run1
- in particular for gluon-gluon
- most important gain for the highest masses
  - for many SUSY searches higher than for dominant SM backgrounds (W, tt)

\[ \sigma(13\,\text{TeV}) / \sigma(8\,\text{TeV}) \]

proton - (anti)proton cross sections

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Extraordinary LHC performance in 2016

- exceeded design value inst. luminosity
- \[ \int \mathcal{L} \ (2016) \] already >> \[ \int \mathcal{L} \ (2015) \]

Experimental challenges

- need to keep trigger rates under control at increasing luminosity
- deal with increasing number of simultaneous collisions
- follow data-taking conditions with on- and offline calibrations
  (particularly important for SUSY measurements – high object multiplicities, select tails of distributions)
Which SUSY flavor?

Potential parameter space is enormous
cMSSM : 4 + 1; pMSSM : 19; MSSM : ~ 105; NMSSM, ...

Concentrate on 3 scenarios

R-parity conserving (lightest SUSY particle = \tilde{\chi}^0_1)
- provides DM candidate
- “classical” SUSY signatures with high missing E_T (MET)
- strong or electroweak production

R-parity violating, different LSPs
- couplings strongly constrained (proton stability)
- loose MET handle for bkg reduction
- alternative signatures like high jet multiplicity

Gauge mediated SUSY breaking
- decay chains terminate with (low-mass, invisible)
- typical signature: MET + \tilde{G} photons or Zs from last decay step
The SUSY hunter’s toolbox

**Standard objects**
- isolated light, tau leptons
- jets, b-tagged jets
- missing energy (energy sum or from jets)

**Kinematic variables**
- $m_T$ (lepton/MET, b/MET)
- $m_{T2}$ (stransverse mass)
- $m_{CT}$ (contrransverse mass)
common feature: endpoint at $m(\text{parent})$

**Hadronic / total energy**
- $H_T$ (scalar sum of (jet) $p_T$s)
- $m_{\text{eff}}$ (sum of jet & lepton $p_T$s, MET)
- $E_T^{\text{sum}}$ (sum of all particle $p_T$s)

**Composite (boosted) objects**
- topness
- boosted W and top taggers
- jet substructure

**Event kinematics**
- hemispheres
- razor / super-razor
- recursive jigsaw reconstruction
Simplified model spectra

THE interpretation tool for SUSY searches @ LHC

Pros
- closely related to exp. observables
  - understand features
- limited number of parameters
  - results as 2D scans
- “easy” reinterpretation (cross-section limit)

Cons
- no complete model
  - consistency, higher-order corrections?
- application to other (full) models
  - ignores details of production, spin structure, ...

A short interpretation guide

Kinematic limit

Expected (median) mass limit
- at nominal production cross section
- 1σ variations due to stat+syst

Map of observed cross section limits
- under assumption BR=1

Observed mass limit
- variations correspond to ±1σ uncertainty on the total production cross section

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GLUINO PAIR PRODUCTION
Gluino decays to bb+LSP

Gluinos: highest SUSY production cross section
• can give access to other sparticles via decay chains
• here: consider decays to two quarks and the LSP

Hadronic search with b-jets
• ≥4 jets, ≥3 b, no lepton (this model)
• key variables: #b-jets, MET, $m_{\text{eff}}$, $m_T$, large-radius jet masses

ATLAS-CONF-2016-052

Other results
• CMS-SUS-16-014
• CMS-SUS-16-015
• CMS-SUS-16-016
Gluino decays to qq+LSP

**Hadronic search**
- two search strategies: $m_{\text{eff}}$ and RJR-based

**Recursive jigsaw reconstruction**
- based on assumption of decay tree
- fix set of rules to resolve combinatorics and unknowns in invisible system
- can form set of variables in the rest frame of each level in the decay tree

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**ATLAS Preliminary**

$\sqrt{s}=13$ TeV, 13.3 fb$^{-1}$

**Data 2015 and 2016**

- SM Total
- Multi-jet
- W+jets
- $t\bar{t}$(+EW) & single top
- Z+jets
- Diboson
- $gg$ direct, $m(\tilde{g}, \tilde{\chi}_1^0) = (1800, 0)$

**Events / 200 GeV**

**Data / MC**

**Other results**
- CMS-SUS-16-014
- CMS-SUS-16-015

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Searches for SUSY
Gluino decays to qq+LSP

Summary of decays to light quarks + LSP

ATLAS-CONF-2016-078

CMS-SUS-16-014
CMS-SUS-16-015

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Searches for SUSY
Gluino decays to $tt+\text{LSP}$

**Hadronic search**
- key variable: $M_{T2}$
- also binned in $\#\text{jets}$, $\#\text{b-jets}$, $H_T$

**Example of background estimation:** irreducible contribution from $Z(\rightarrow \nu\nu)+\text{jets}$

**Jet multiplicity for a signal-enriched region**
Gluino decays to $tt+\text{LSP}$

**CMS summary**

$\mathcal{P} p \rightarrow \tilde{g}\tilde{g}$, $\tilde{g} \rightarrow \mathcal{H}^{\text{res}}$, $12.9 \text{ fb}^{-1}$

**ATLAS multi-b**

$\mathcal{P} p \rightarrow \tilde{g}\tilde{g}$, $\tilde{g} \rightarrow \mathcal{M}^{\text{res}}$, $14.8 \text{ fb}^{-1}$

**Other results**

- ATLAS-CONF-2016-037
Gluino production / chargino

Alternative decay chains in gluino production
• decays via a chargino and a $W(*)$

Single lepton search
CMS-SUS-16-019
• 1 lepton, jets, (here no) b-jets
• key variables: $H_T$, MET, “$W$” $p_T$, and $\Delta\phi(\text{"W"},\text{lepton}$

Same-sign dileptons
CMS-SUS-16-020
• small SM backgrounds (multi-boson, fake leptons, charge flip)
• binned in $p_T(l)$, $m_T$, MET, $H_T$, #jets

Other results
• ATLAS-CONF-2016-078
• ATLAS-CONF-2016-054
• CMS-SUS-16-014
• CMS-SUS-16-022

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SQUARK PAIR PRODUCTION
Top squarks

Low-mass top squarks required for natural models
• could be the 2\textsuperscript{nd} lightest SUSY particle (and the first detectable sparticle at the LHC)

Signature
• favored decay via $t^{(*)}$ and LSP: final states classified according to W decay mode
• approaches SM $tt$ signature for $\Delta m \approx m(t)$ and low LSP mass

4-body decay

Decay via on-shell top quarks (2 body)

alternative: flavor-changing decays via charm

Decay via on-shell W (3 body)

if chargino is accessible: alternative decay to $b$-chargino
Top squarks

**Hadronic search**

- optimizations for low and high $\Delta m$
  - high $\Delta m$: using #jets, #b-jets, $m_T(b)$, and MET; #tops and #Ws from jet substructure

**Other results**
- ATLAS-CONF-2016-077
- CMS-SUS-16-029
- CMS-SUS-16-030
  + various inclusive searches

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**CMS-SUS-2016-029**

- $12.9 \text{ fb}^{-1}$ (13 TeV)

- **Events**

  - CMS Simulation
  - CMS Preliminary

  - $M_T(b_{1,2}, E_T) < 175$ GeV
    - $N_b \geq 7$
    - $N_W = 0$, $N_{Z} = 0$

  - $M_T(b_{1,2}, E_T) > 175$ GeV, $N_b \geq 2$
    - $N_W \geq 1$
    - $N_{Z} \geq 1$

- Bkg. Uncertainty

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Top squarks

Single-lepton search
- basic selection on jets, b-jets, MET
- signal regions optimized for different \( \Delta m \) and stop decays

**ATLAS-CONF-2016-050**

### ATLAS.png

Dilepton search (ATLAS)
- basic selection on 2 OS leptons
- use of derived observables - super-razor, \( M_{T2} \)

**ATLAS-CONF-2016-076**

Distributions in one of the 1l signal regions

exclusion for 3-body decays

Other results
- CMS-SUS-16-029
- CMS-SUS-16-030
+ various inclusive searches

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Searches for SUSY
Top squarks (the soft side)

**Direct production**
- $\Delta m < m(W)$: experimentally challenging but could explain DM density due to co-annihilation
- handles: ISR jets, soft leptons

**Hadronic** CMS-SUS-16-029

**2 leptons** CMS-SUS-16-025

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Top squarks – alternatives

Lightest top squark might be undetectable in direct production
• search in decay chains!

Hadronic search
• specific search region for highly boosted top quarks:
  uses mass of reclustered jets (R=1.2)

3-lepton + b search
• Z-decay + 3\textsuperscript{rd} lepton
• other variables: #jets, #b, MET, p_{T}(Z)
Top squarks - summaries

ATLAS summary

CMS 0l+1l combination for 2-/3-body decay

ATLAS Preliminary
- $t\bar{t}_1 \rightarrow b t \tilde{\chi}^0_1$/$t\bar{t}_1 \rightarrow c \tilde{\chi}^0_1$/$t\bar{t}_1 \rightarrow W b \tilde{\chi}^0_1$/$t\bar{t}_1 \rightarrow t \tilde{\chi}^0_1$

Status: ICHEP 2016

CMS Preliminary
- $pp \rightarrow \tilde{t}_1 \tilde{t}_1^* \rightarrow t \tilde{\chi}_1^0$ NLO+NLL exclusion

- Observed $\pm 1 \sigma_{\text{theory}}$
- Expected 0l analysis
- Expected $\pm 1 \sigma_{\text{exp.}}$
- Expected 1l analysis

95% CL upper limit on cross section (pb)
Opposite-sign dilepton search

• Opposite-sign ee or μμ pair with jets and MET
• Here: off-Z regions targeting kinematic edge in decay chain
• dominant flavor-symmetric backgrounds estimated from data
• SRs binned acc. to tt discriminator, #jets, #b-jets, MET

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ELECTROWEAK PRODUCTION MODES
Chargino / neutralino production

Direct production of “electroweakino” pairs
• decays via sleptons / sneutrinos
• using benchmarks to illustrate different scenarios (depend on mixings and nature of lightest slepton)

Multilepton searches
• 3 (or 4) leptons (includes combinations with 1 or 2 hadronically decaying τs)
• SRs binned in flavour&charge combination, MET, m(II)/p_T(II)

Effect of change in intermediate slepton mass

Other results in EW prod.
CMS-SUS-16-021
CMS-SUS-16-025
CMS-SUS-16-026

3l + same-sign 2l
Chargino / neutralino production

Strong motivation for small mass splittings in natural SUSY
- $\tilde{\chi}^\pm_1$ and $\tilde{\chi}^0_2$ degenerate, $\tilde{\chi}^0_1$ only slightly lighter

Soft dilepton search
- need very low lepton $p_T$ ($\geq 3.5$-5 GeV)
- combination of pure MET & specific $2\mu$+MET triggers
- other selections: MET, $H_T$, b-jet veto

Dilepton mass spectrum
for low and high MET

CMS-SUS-16-025
GMSB Scenarios
Gluino-induced Z/$\gamma$+gravitino

**Photons + jets search**
- $\geq 1 \gamma$, jets, MET, 0 leptons
- key variables: $n_{\text{jets}}$, $m_{\text{eff}}$, jet hierarchy
- 2 signal regions optimized for high and low gluino/NLSP splitting

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**Also:**
- specific search for $t$ squark → $\tau$ slepton cascades

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Other GMSB results.

CMS-SUS-16-021
R-parity Violation
RPV in gluino or squark decays

Decays proceed via $B\#$ violating couplings $\lambda''$
- Assume unchanged production, and prompt decays

Same-sign dilepton / 3 lepton search
- several signal regions sensitive to RPC and RPV models
- here: $\geq 2$ leptons, $\geq 1$ b-jet, $\geq 2$ jets, $m_{\text{eff}}$, no MET requirement

**ATLAS-CONF-2016-037**

Other results
**ATLAS-CONF-2016-084**

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RPV / EW production

RPV in electroweak production
• decay via L#-violating coupling \( \lambda \)

Search in 4-lepton events
• backgrounds from rare SM processes (ttX, multi-boson), fake leptons
• 2 signal regions with different \( m_{\text{eff}} \) requirements

**Figure 1:** Diagram of the benchmark SUSY model of chargino production with indirect RPV decays.

In the benchmark model considered for this analysis, wino-like charginos are pair-produced, and the LSP is a bino-like neutralino. The charginos decay to the LSP while emitting a \( W \) boson, as shown in Figure 1.

The subsequent chargino decay is mediated by the \( \lambda_{ijk} L_i L_j \bar{E}_k \) term in Eq. \( 1 \), allowing each LSP to undergo a lepton-number-violating RPV decay:

\[
\tilde{\chi}_1^0 \rightarrow \ell^+ \ell^- \nu \nu \text{, with the allowed lepton flavours depending on the indices of the associated } \lambda_{ijk} \text{ couplings.}
\]

Thus, every signal event contains a minimum of four charged leptons, and potentially up to six if both \( W \) bosons decay leptonically.

In principle, the nine \( \lambda_{ijk} \) RPV couplings allow the charginos to decay to every possible combination of charged lepton pairs. The scenarios considered here include decays to electrons and muons only, with a branching fraction of \( \frac{1}{3} \) each for

\[
\tilde{\chi}_1^0 \rightarrow e^+ e^- \nu \nu, \tilde{\chi}_1^0 \rightarrow e^\pm \mu^0 \nu, \tilde{\chi}_1^0 \rightarrow \mu^+ \mu^- \nu
\]

The \( \lambda_{121} \) and \( \lambda_{122} \) couplings can produce these chargino decays, therefore we refer to these SUSY scenarios as \( \text{LL} \bar{E}_{12} \) \((k = 1, 2)\). However, the chargino branching fractions cannot be reproduced by a single non-zero \( \text{LL} \bar{E} \) coupling. Instead, interpretations in “pure” coupling scenarios can be obtained by appropriate reweighting of the simulated events, analogous to the procedures used in Ref. [31].

Chargino masses of 500–1200 GeV are studied for the \( \text{LL} \bar{E}_{12} \) scenarios, where the LSP masses range from 10 GeV \( \lesssim m(\tilde{\chi}_1^0) \lesssim m(\tilde{\chi}_1^\pm) \) 10 GeV to ensure both the RPC cascade and the RPV LSP decay are prompt. Over this chargino mass range, the \( \tilde{\chi}_1^+ \tilde{\chi}_1^- \) production cross-section varies from about 22 fb to about 0.2 fb \([32, 33]\).

The ATLAS detector [34] is a multipurpose particle physics detector with forward-backward symmetric cylindrical geometry. The inner tracking detector (ID) covers |\( \eta | < 2.5 \) and consists of a silicon pixel ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the \( z \)-axis along the beam pipe. The \( x \)-axis points from the IP to the center of the LHC ring, and the \( y \)-axis points upward.
RPV in gluino production

RPV in gluino decays
- decay via B#-violating couplings $\lambda''$

Multijet search
- bkgs from rare SM processes, fake leptons
- 2 regions with different $m_{\text{eff}}$ requirements

Competitive limit from CMS-SUS-16-013 (2015), but for exclusive decays to tbs!

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SHORT LOOK BACK TO RUN1
Link with full models: pMSSM

Phenomenological MSSM
- catches essential MSSM features in 19-dim subspace
  - assumptions: no CPV couplings, R-parity conserving, degeneracy of 1st & 2nd generation, MFV
- goal: understand impact on model parameters, limitations of SMS approach & “holes” in experimental MSSM coverage using scans of pMSSM parameter space

Impact of CMS searches
- Bayesian analysis including 11 CMS analyses @ 7 and 8 TeV

CMS, arXiv:1606.03577

Impact of CMS searches
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CMS, arXiv:1606.03577

Other exp. pMSSM study: ATLAS, JHEP 10 (2015) 134
Link with full models: pMSSM DM study

**EWKH model**
- pMSSM reduced to 5 parameters: $M_1, M_2, \mu, \tan\beta, m_A$
  - quarks and sleptons are decoupled

**Impact of ATLAS searches**
- 4 di- and multi-lepton analyses
- constraints from direct DM searches, relic density, flavor physics, ...

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**ATLAS, arXiv:1608.00872**

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**ATLAS Simulation**
Samples from the initial likelihood scan
EWKH model

**ATLAS**
Samples from the initial likelihood scan
Excl. by Run-1 2$\ell + 3\ell + 4\ell$
EWKH model

**direct impact on $M_1$, to a lesser extent $M_2$ & $\mu$**

$m(\tilde{\chi}_1^\pm)$ [GeV]

$\Omega \chi h^2 \sim 10^{-2}-10^{-1}$, low $\sigma_{SI}^\chi N$
Summary

- Excellent LHC performance allowed for considerable increase in sensitivity with partial 2016 data set
  - Experiments performed a large set of analyses almost synchronously with data taking
- Searches now extended to more challenging scenarios
  - Electroweak production, compressed mass spectra, ...
  - Can expect many more after end of 2016 data taking!
- Mass limits (in simplified model spectra!)
  - pushed to about 1.9 TeV (gluinos) and 900 GeV (top squarks); limits on EW production even for small mass differences

Much larger data sets will be available at the end of 2016 and during the rest of Run2, and we are looking forward to seeing first significant deviations from SM predictions!
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Light & b squark production

Hadronic analysis / strong production
- low #jets SRs targeting direct production

Inclusive hadronic analysis
- multijet rejection: $\alpha_T$
- SRs binned in #jets, #b jets, $H_T$

ATLAS-CONF-SUSY-2016-078

CMS-SUS-16-016

Other results
CMS-SUS-16-014
CMS-SUS-16-015
Top squarks – alternative decays

Hadronic search

- Using top-tagger for wide $p_T$ range (using 1-3 R=0.4 jets)

Decay via chargino

- interpretation exists for 0l, 1l, 2l channels

Here: single-lepton search

Other results

- ATLAS-CONF-2016-077
- ATLAS-CONF-2016-076
- CMS-SUS-16-028
- CMS-SUS-16-029
Summaries strong production (ATLAS)

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Summaries EW production (CMS)

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Summaries squark production (CMS)

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Summaries gluino production (CMS)